Indices of Climate Change for the United States

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ABSTRACT

A framework is presented to quantify observed changes in climate within the contiguous United States through the development and analysis of two indices of climate change, a Climate Extremes Index (CEI) and a U.S. Greenhouse Climate Response Index (GCRI). The CEI is based on an aggregate set of conventional climate extreme indicators, and the GCRI is composed of indicators that measure changes in the climate of the United States that have been projected to occur as a result of increased emissions of greenhouse gases.

The CEI supports the notion that the climate of the United States has become more extreme in recent decades, yet the magnitude and persistence of the changes are not large enough at this point to conclude that the increase in extremes reflects a nonstationary climate. Nonetheless, if impacts due to extreme events rise exponentially with the index, then the increase may be quite significant in a practical sense. Similarly, the positive trend of the U. S. GCRI during the twentieth century is consistent with an enhanced greenhouse effect. The increase is unlikely to have arisen due to chance alone (there is about a 5% chance). Still, the increase of the GCRI is not large enough to unequivocally reject the possibility that the increase in the GCRI may be the result of other factors, including natural climate variability, and the similarity between the change in the GCRI and anticipated changes says little about the sensitivity of the climate system to the greenhouse effect. Both indices increased rather abruptly during the 1970s, a time of major circulation changes over the Pacific Ocean and North America.

1. Introduction

Has the climate changed significantly during the century that is about to end? If so, in what ways and how much? Climatologists are struggling to answer such questions, not only for scientific interests but also to aid policy makers (IPCC 1995) and the public at large. Answers to these questions are fundamental for developing confidence about global and regional projections of climate into the next century. Such confidence is important not only to scientists concerned with issues of climate sensitivity to anthropogenic and natural climate forcings and feedbacks but also to policy makers, nonspecialists, and the general public. They all require comprehensive, yet intuitive, information that allows them to understand the scientific basis for confidence, or lack thereof, in the present understanding of the climate system.

In this article, our primary focus relates to the problem of summarizing and presenting a complex set of multivariate, multidimensional changes such that they can be readily understood and used in policy decisions made by nonspecialists in the field. We selected the contiguous United States as the focus of analysis. The reasons are 1) it is of special concern to U.S. citizens and policy makers, 2) the changes of climate within the United States have not been given extensive coverage in intergovernmental or national reports that focus on climate change assessments (IPCC 1990, 1992; NRC 1992), 3) the errors and systematic biases of data from the United States have been well studied (Karl et al. 1986; Karl and Williams 1987; Karl et al. 1988; Quayle et al. 1991; Karl et al. 1993a; Karl et al. 1993b; Groisman and Easterling 1994), and 4) the climate records for this area are of sufficient

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length that high frequency climate variability is less likely to obscure low frequency climate variations and changes.

2. Data

Twentieth century changes and variation of precipitation with monthly resolution can be calculated from the National Climatic Data Center's climate division database (Guttman and Quayle 1996). This dataset consists of thousands of first-order and cooperative weather observing sites across the country but only a fraction of these continue through 1994. Although there are likely to be significant precipitation measurement biases at each of these stations (Karl et al. 1993a,b; Groisman and Easterling 1994), mainly in the form of solid precipitation undercatch, the time-varying biases are likely to be considerably smaller. This is because in this database most of the sites have had fairly consistent instrumentation, such as standard 8-in. unshielded gauges. Moreover, comparisons with other datasets (Karl et al. 1993a; Groisman and Easterling 1994) depict only small differences in precipitation trends. Nonetheless, Legates (1995) argues that during months with both liquid and solid precipitation, a systematic change in the ratio of liquid to solid precipitation could introduce an undetected time-varying bias. More work remains to be done to fully assess the significance of this potential bias, but related streamflow data (Lins and Michaels 1994; Lettenmaier 1994) would suggest that such a bias is unlikely to adversely affect this assessment of precipitation trends during the twentieth century.

A common tool used to quantify long-term moisture anomalies in the United States is the Palmer Drought Severity Index (PDSI). The PDSI categorizes moisture conditions in increasing order of intensity as near normal, mild to moderate, severe, or extreme for drought or wetness. The PDSI is affected by both long-term moisture shortages and excesses and by variability of temperature-driven evaporation from soils and transpiration (release of water vapor) from plants. Since warmer conditions are capable of causing more water to evaporate from the earth's surface, both temperature and precipitation affect the drought index, but temperature anomalies are less a factor than direct changes in precipitation. The National Climate Data Center climate division precipitation and temperature database are used to calculate the PDSI (Karl 1986).

Twentieth century changes of mean maximum and minimum temperature with monthly resolution are calculated from the U.S. Historical Climatology Network (HCN) (Karl et al. 1990). This database has over 1200 stations, with records from many of the stations beginning in the late nineteenth or early twentieth centuries. Over 600 continuous well-distributed observing sites across the United States were selected based on the number of potential discontinuities (any change in instrument siting, location, or instrument type), the consistency of their trends with those of nearby stations, the percentage of missing data, and the width of the confidence interval of the adjustment applied to the data and the record length (Karl et al. 1990). Each station used was adjusted: a priori adjustments included observing time biases (Karl et al. 1986), urban heat island effects (Karl et al. 1988), and the bias introduced by the introduction of the maximum–minimum thermistor and its instrument shelter (Quayle et al. 1991); a posteriori adjustments included station and instrument changes (Karl and Williams 1987).

Daily changes of precipitation were derived from a subset (131) of the HCN stations and supplemented with non-HCN stations in the West where coverage was sparse. The supplemental stations were selected outside of urban areas and had consistent observing times, whereas stations in the HCN had a limited number of random (not systematic) changes in observing times (Hughes et al. 1992).

3. Statistical methods

For each indicator or index,[1] we test the hypothesis that the magnitude of the observed trend is a byproduct of a quasi-stationary climate. The term "quasi-stationary" is used to reflect the notion that over very long timescales (thousands of years) no climate regime is likely to be stationary. The alternative hypothesis is that the observed trend represents a changing climate. Each time series is fit to an autoregressive moving average (ARMA) model (Box and Jenkins 1976). Such a model can account for a wide variety of stationary (and apparent nonstationary) processes (Priestly 1981), including periodicities, persistent fluctuations, quasi periodicities, etc. The model can be written in the form

[1]An index is defined as an aggregate of a set of indicators.

$$Y_t = \sum_{i=1}^{p} \phi_i Y_{t-1} + \sum_{j=1}^{q} \theta_j a_{t-j} + a_t, \qquad (1)$$

where Y_t is the value of the time series at time t, ϕ_i is the ith autoregressive (AR) coefficient, θ_j is the jth moving average (MA) coefficient, and a_t is random noise at time t. The order of the model is expressed as p, q and represented as ARMA (p, q). The distribution of a_t is normal with mean zero and standard deviation σ_a (i.e., the standard deviation of the random noise).

When p and q are zero, the model represents a white noise or uncorrelated serial process. ARMA (0, q) models can be characterized as having finite persistence. That is, the random noise in the model persists for exactly q observations. By comparison, ARMA (p, 0) models can be characterized as having infinite but exponentially decaying persistence of the random noise component. Karl (1988) contains more details on the climatological applications of this model.

The Bayesian Information Criterion (BIC) was used to select the appropriate order of the model (Katz 1982). The BIC balances the goodness of fit against the complexity (the order) of the model. The model with the smallest BIC is preferred. The sensitivity of our results is tested by also considering the model with the second smallest BIC. Models were constrained such that $p + q \leq 4$, with higher-order models tested only if BIC reached a minimum at model order 4. This assumption is consistent with the notion that highly complex statistical models are likely to overfit the observations (i.e., attach too much significance to the noise within the data).

The trend is removed from each time series prior to fitting the model. This is necessary because our interest will be in using the model to simulate a stationary process and compare this to the observed trends. Once the appropriate model is identified for each indicator or index, the trend of the observed time series is compared with trends calculated from 1000 Monte Carlo simulations from generated time series of an ARMA model. Each time series has the same number of discrete values as does the observed indicator or index of interest. The fraction of time that the observed trend exceeds those calculated from the simulated series is used as a measure of the statistical significance of the observed trend.

Numerous indicators are considered, and although we provide estimates of their statistical significance, their interpretation can sometimes become difficult. This is because as more and more indicators are analyzed, it is likely that some will contain unusual trends simply due to chance. This is one of the prime motivations for developing an index that integrates a variety of climate change indicators.

4. Background

Area-averaged total precipitation has varied from decade to decade (Fig. 1). This area-averaged value is derived from area weighting the total annual precipitation from each of the 344 climate divisions across the United States. Although there is an absence of a monotonically increasing trend, since about 1970 precipitation has tended to remain above the twentieth-century mean and has averaged about 5% more than in the previous 70 years. Such an increase hints at a change in climate. Formal statistical analysis suggests that the change is unusual, but still there is about a 10% chance that such a change could arise from a quasi-stationary climate without any real long-term changes. The end-of-century increase is mainly due to increases during the second half of each year, particularly during the autumn. On a regional basis (Fig. 2), we see that the increase is widespread within the United States, and local increases of nearly 20% are not uncommon. The increase is not apparent everywhere, however, as some states like California, Montana, Wyoming, North Dakota, Maine, New Hampshire, and Vermont, as well as parts of the Southeast, have had decreases in annual precipitation.

As is the case with precipitation, mean temperatures across the United States have not monotonically increased during the present century (Fig. 3), although

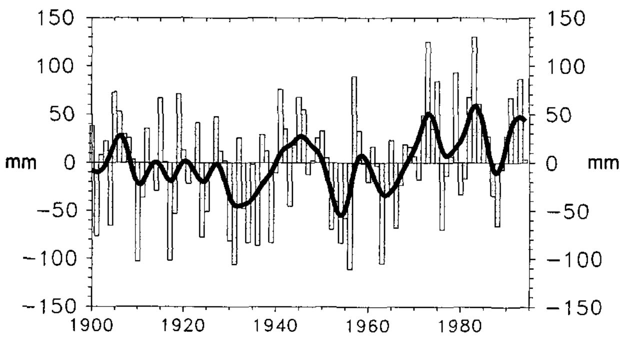

FIG. 1. Departures from the long-term mean of area-average annual precipitation over the conterminous United States. The smooth curve on this and subsequent plots is generated from a nine-point binomial filter of the annual values. The data end in 1994 for this and subsequent figures.

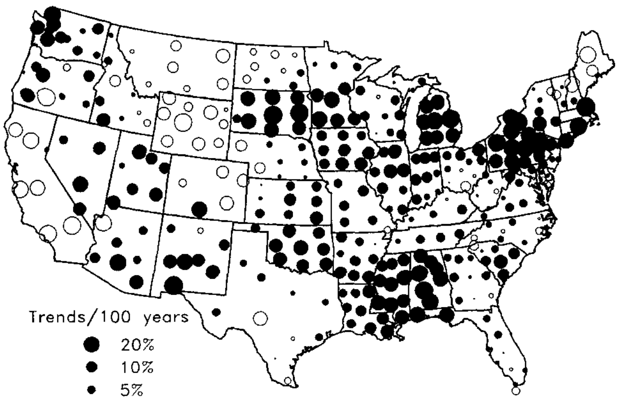

FIG. 2. Precipitation trends (1900–94 converted to percent per century) centered within state climatic divisions are reflected by the diameter of the circle centered within each climatic division. Solid circles represent increases and open circles, decreases.

a linear trend equates to a rise of about 0.4°C (100 yr)$^{-1}$. Such a simple interpretation of mean temperature change in the United States would be a gross oversimplification. The records reveal a sharp rise in temperature during the 1930s and a modest cooling from the 1950s to the 1970s, at which time the temperature increased and has since remained as high as some of the high temperatures recorded during the major droughts of the 1930s. However, the more recent warmth is accompanied by relatively high amounts of precipitation, unlike the dry 1930s. Although U.S. temperatures have substantially increased, the increase by itself is neither large enough nor temporally consistent enough to completely dismiss the notion (around 1 chance in 20) that the change may have arisen due to purely random natural variations.

The increase in annual temperatures after the 1970s is mainly the result of significant increases of temperature during the first six months of the year (winter and spring). Temperatures during summer and autumn have changed little after dropping from those of the warm 1930s.

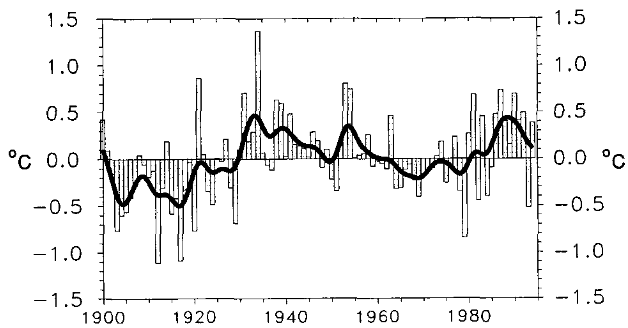

FIG. 3. Same as Fig. 1 except for mean temperature in °C.

On a regional basis, the areas north and west of an arc from Virginia through Illinois to Texas contribute most to the increase of annual average nationwide temperatures (Fig. 4), while the Southeast shows mostly cooling. There has been a tendency for smaller temperature increases to be coincident with the larger positive trends of precipitation and also to be associated circulation changes (Trenberth and Hurrell 1994).

5. Indicators of climate change for the United States

Twentieth century changes in a variety of climate indicators that represent various aspects of climate are presented in the next two subsections. Each indicator has been selected based on its reliability, length of record, updateability, and its relevance to changes in climate extremes or projected climate responses due to increasing anthropogenic greenhouse gases.

a. Extremes

An important aspect of climate extremes relates to extreme droughts and moisture surpluses. To characterize long-term variations of drought or wetness, it is possible to calculate the proportion of the United States under conditions of severe and extreme (which we simply characterize as "severe") drought or moisture surplus, as defined by the PDSI. Considerable decadal variability of drought and wetness is revealed (Fig. 5). The droughts of the 1930s and 1950s stand out in the upper curve as remarkable events. During 1934, the most extreme year, nearly 50% of the country on average was in severe drought; even the spring and summer drought of 1988 was dwarfed by com-

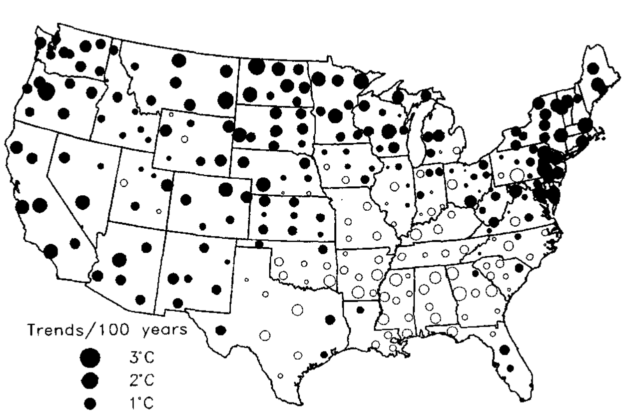

FIG. 4. Same as Fig. 2 except for mean temperature [°C (100 yr)$^{-1}$]. Closed circles represent warming and open circles cooling.

parison. Since about 1970, however, more of the country has tended to remain excessively wet: over 30% of the country has experienced a severe moisture surplus for at least one year in each of the past three decades. The catastrophic summertime flooding of the Mississippi River and its tributaries in 1993 was an obvious example of these severe moisture surplus events, but Table 1 indicates that there is still a good chance (about 25%) that the trend toward increased frequency of severe moisture has arisen from a quasi-stationary climate with exponentially decaying persistence.

The national effects of a long-term moisture deficit or surplus are generally proportional to the areal coverage in either severe drought or severe moisture surplus. If we consider the sum of the proportion of the country in either of these severe categories, no systematic trends are evident in the present century, although during the past few decades, there has been a tendency for a greater portion of the country to be either in severe drought or severe moisture excess.

TABLE 1. Estimated statistical significance based on the best (left) and second best (right) ARMA models for various indicators related to climate extremes. The hypothesis tested is that trends this century are not stationary.

Indicator (Percentage of United States)	Sign of trend	Model order ARMA (p, q)	P-value of trend
In severe/extreme drought	–	(1, 2)/(1, 0)	0.85/0.83
With severe/extreme moisture surplus	+	(2, 1)/(0, 1)	0.28/0.21
With mean *maximum* temperatures much *below* normal	–	(1, 0)/(0, 2)	0.01/0.02
With mean *maximum* temperatures much *above* normal	+	(1, 1)/(1, 0)	0.62/0.47
With mean *minimum* temperatures much *below* normal	–	(1, 1)/(1, 2)	0.06/0.07
With mean *minimum* temperatures much *above* normal	+	(1, 2)/(2, 2)	0.46/0.51
With much *above* normal number of wet days (measurable precipitation)	+	(1, 2)/(2, 1)	< 0.001/< 0.001
With much *above* normal number of dry days (no precipitation)	+	(0, 1)/(0, 2)	0.48/0.46
With much *above* normal proportion of precipitation from extreme (> 50.8 mm) 1-day precipitation events	+	(1, 1)/(1, 2)	< 0.001/< 0.001

*Probability that the trend is a random realization of a stationary climate.

As with drought and excessive moisture, portions of the country can be extremely cold at the same time that others are unusually warm. This is actually a fairly common occurrence because the conterminous United States very roughly spans half the average longitudinal extent of a stationary Rossby wave—for example, the Pacific North American teleconnection pattern—thus placing one part of the country in southerly flow and the other in northerly flow. This leads to an average national temperature that is near normal. Hence, we focus on temperature indicators that can capture changes in unusually cold or warm weather, even when average national temperatures are near normal. Also, abnormally high daytime maximum temperatures can occur while nighttime temperatures remain below normal (this is not usually the case, however), or vice versa. Moreover, an increase (decrease) of temperature can be asymmetric in the tails of the distribution. For example, the warmth of the 1930s is better reflected by the area of the country affected by much above normal[2] annual daily maximum tempera-

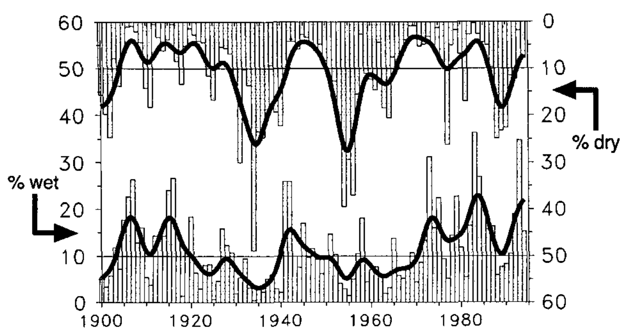

FIG. 5. Percentage of the conterminous U.S. area in severe moisture surplus (bottom curve, left scale) and in severe drought (top curve, right scale).

[2]Defined as being within the upper 10% or upper decile of all annual values.

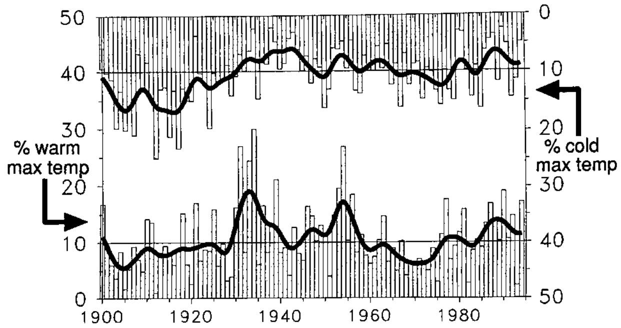

FIG. 6. Percentage of the conterminous U.S. area with much above normal (bottom curve, left scale) or much below normal (top curve, right scale) monthly mean maximum (max) temperatures.

tures (Fig. 6) compared with the percentage of the country affected by much above normal annual minimum temperatures (Fig. 7). Figure 7 also shows that the proportion of the United States with much below normal mean annual daily minimum temperatures has been sustained at low levels since the late 1970s, with only a 5% to 10% chance that the overall decrease in the area affected by these conditions would occur in a stationary climate (Table 1). Even more striking is the decrease in area affected by much below normal conditions of the maximum temperature (Fig. 6; Table 1) with only a 1% or 2% chance occurrence. The recent increase of the minimum temperature relative to maximum temperature has been related directly to an observed increase in cloud amount over the past several decades (Plantico et al. 1990).

The modest increase in the fraction of the country with much above normal monthly maximum *or* minimum temperatures (Table 1) has been more than compensated by the clear trend toward fewer areas with much below normal temperatures.

An analysis of changes in extremes would be incomplete without consideration of changes in daily precipitation events. The proportion of the country with a much greater than normal number of wet days (Fig. 8) has increased much more than would be expected in a stationary climate (Table 1). This is especially apparent between 1910 and 1940 and after about 1970. The latter increase bears some similarity to the increase of total precipitation over the United States (Fig. 1). Meanwhile, the proportion of the United States with a much greater than normal number of dry days has shown little overall change. Occasionally, for certain areas and times of the year, there are too few wet days in a given month to establish an upper tenth percentile. These areas are not included.

The proportion of the country that has had a much greater than normal amount of precipitation derived from extremely heavy (> 50.8 mm or 2 in.) 1-day precipitation events (Fig. 9) can be reliably calculated back at least to 1910. As similarly shown in Fig. 8, in some regions and for certain months of the year, 1-day precipitation events exceeding 50.8 mm never occur—for example, the West in summer. These areas and months of the year are not included in the indicator. It is clear (Fig. 9) that during the present century there has been a steady increase in the area of the United States affected by extreme precipitation events. It is unlikely (less than 1 chance in 1000) that such a large change could occur in a quasi-stationary climate (Table 1). It is noteworthy that similar trends arise for other lower bounds of heavy precipitation, for example, 25.4 mm.

Other measures of high frequency extreme events were also considered, such as the frequency of heat waves and cold waves, freezes, strong winds, tropical cyclones, etc. but were not included in the Climate Extremes Index (CEI) at this time. With appropriate data, these additional measures could easily be used,

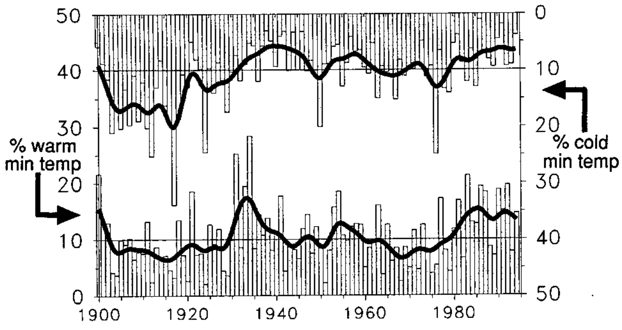

FIG. 7. Same as Fig. 6 except for minimum (min) temperature.

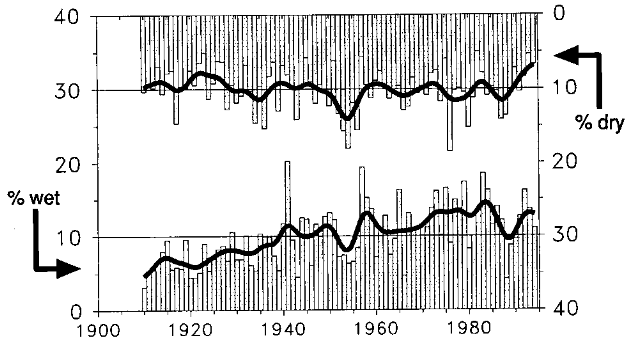

FIG. 8. Percentage of the conterminous U.S. area with the number of wet days much above normal (bottom curve, left scale) or number of dry days much above normal (top curve, right scale).

but existing datasets require considerably more attention with respect to homogeneity. Even today, however, the frequency of daily temperature above a given threshold cannot be reliably calculated for large portions of the United States. Proper adjustments for changing observing times at daily resolutions have not been developed. Fortunately, there is a high correlation between much below (or above) normal conditions and cold waves (heat waves), which last several days. The duration, intensity, and areal extent of tropical and extratropical cyclones also require more homogeneity assessment, as do the frequencies of tornadoes and hail.

b. Greenhouse response

Efforts to detect the effects of greenhouse gas warming are best studied through global analyses (Karl 1993). Such analyses have been made and assessed in both intergovernmental (IPCC 1990, 1992, 1995) and national reports (NRC 1992). The most recent commissioned IPCC assessment has concluded that observed changes in global climate indicate an emerging pattern of climate response to anthropogenic increases of greenhouse gases and sulfate aerosols. The question arises, however, whether there is any evidence to suggest that the expected effects of anticipated greenhouse warming are already affecting the climate of the United States. A number of projections have been made that are expected to affect large continental regions in the mid-to-high latitudes, such as the United States (IPCC 1990, 1992, 1995). These changes, in rough order of confidence in the projections (IPCC 1990, 1992, 1995), include

- an increase of mean surface temperature;
- an increase in precipitation, primarily in the cold season;
- more severe and longer lasting droughts, especially during the warm season (May–September);
- a small but significantly greater increase of nighttime temperature than daytime temperature;
- a greater portion of precipitation derived from heavy precipitation as opposed to gentler, longer-lasting precipitation; and
- a decrease in the day-to-day variability of temperature.

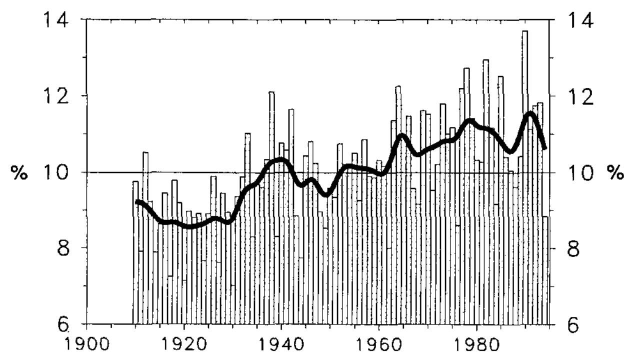

FIG. 9. Percentage of the conterminous U.S. area with a much above normal proportion of total annual precipitation from 1-day extreme (more than 2 in. or 50.8 mm) events.

The increase in the mean temperature is a fundamental characteristic of all model simulations with enhanced greenhouse gases, with the daily minimum temperature increasing about 10% more than the maximum. Another primary climatic response to increased greenhouse gases relates to an intensified hydrologic cycle. As a result, cold season precipitation generally increases in the mid-to-high latitudes, as a warmer atmosphere is capable of maintaining greater amounts of water vapor condensed as precipitation in migrating cyclones. During summer, increased surface temperatures leads to greater evaporation with only small changes in precipitation in some areas and more frequent and severe droughts. An increase in convective precipitation, resulting in more intense rainfalls (not necessarily more overall rain), is also a characteristic of a stronger hydrologic cycle. The projected reduction in the day-to-day temperature variability in a warmer climate is consistent with the reduced day-to-day variability of temperature in the summer versus the winter and in the Tropics compared to middle and high latitudes. Warmer sea surface temperatures alone could be expected to increase the severity and/or frequency of hurricanes affecting the United States and adjacent waters. However, the natural variability of hurricanes is so great (Karl et al. 1995a) and model projections so uncertain that even century-scale changes are not reliable indicators of greenhouse warming.

The projected changes have been captured in five climate indicators, as listed in Table 2. One of these, the increasing proportion of the country with extreme 1-day precipitation events, has also been considered as being related to changes in extremes (Table 1). In addition to the increase in the area affected by much above normal mean temperatures (Fig. 4) and the proportion of the United States affected by extreme precipitation events, the percentage of the United States affected by much above normal cold season precipitation has significantly increased since 1970 (Table 2 and Fig. 10). In contrast, the proportion of the coun-

TABLE 2. Same as Table 1 except indicators are related to projected large-scale changes associated with an enhanced greenhouse effect. The hypotheses tested are that trends this century are not stationary and are positive. Here, T_{mx} is the mean maximum temperature and T_{mn} is the minimum.

Indicator (Percentage of United States)	Sign of trend	Model order ARMA (p, q)	P-value of trend
With much *above* normal mean temperatures ($0.525*T_{mx} + 0.475*T_{mn}$)	+	(1, 2)/(1, 1)	0.27/0.21
With much *above* normal precipitation during the cold season (Oct. through Apr.)	+	(1, 0)/(0, 1)	0.01/0.01
In extreme/severe drought during the warm season (May through Sept.)	+	(1, 0)/(1, 1)	0.45/0.42
With much *above* normal proportion of precipitation from extreme (> 50.8 mm) 1-day precipitation events	+	(1, 1)/(1, 2)	< 0.001/< 0.001
With much *below* normal day-to-day temperature differences	+	(1, 1)/(2, 1)	0.14/0.12

try affected by extreme and severe warm season droughts reflects little overall trend but considerable decadal variability (Fig. 11).

Changes in high frequency temperature variability can be reflected in the day-to-day changes of temperature calculated as the absolute value of the difference in temperature from day i to day $i + 1$. Trends in the proportion of the United States with much above (below) normal day-to-day temperature change for the present century indicate that there has been a rather steady and significant decline (increase) in the area affected by these abnormally high (low) day-to-day differences of temperature. The reduction in day-to-day temperature variability is not as apparent in the much below normal category of day-to-day temperature differences (Fig. 12) but still has a positive trend (Table 2) and relatively small P values.

6. Climate change indices

It should be clear by now that not only is it difficult to assimilate the broad spectrum of changes in various indicators related to the U.S. climate but conveying this information to policy makers and the general public is a formidable task. For these reasons, an index that combines a number of climate indicators related to a specific aspect of climate change can provide a convenient tool for summarizing the state (and changing state) of the climate. To be useful, it must have a clear meaning, a moderately long history, and continuity into the future. It should not smooth out potentially important aspects of climate change in the name of intended simplification. Two types of indices have been developed. The first is aimed at assessing changes and variations of climate extremes and is most relevant to gauging the potential impact of long-term climate variations and changes on natural and man-made systems in the United States. The other focuses on changes that have been projected to occur in the United States as a result of anthropogenic increases in greenhouse gases.

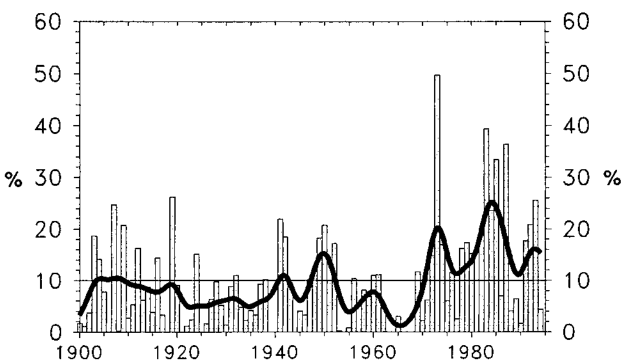

FIG. 10. Percentage of the conterminous U.S. area with much above normal cold season (Oct. through Apr.) precipitation.

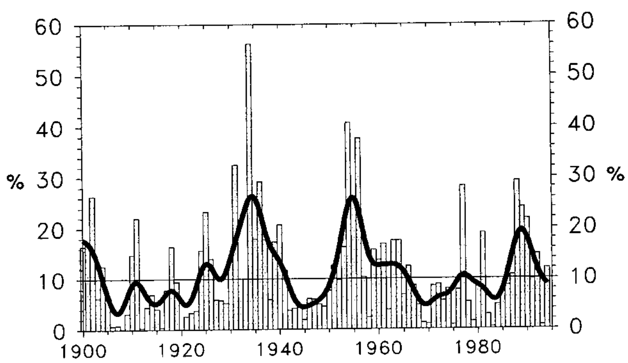

FIG. 11. Percentage of the conterminous U.S. area in severe or extreme drought during the warm season (May through Sep.).

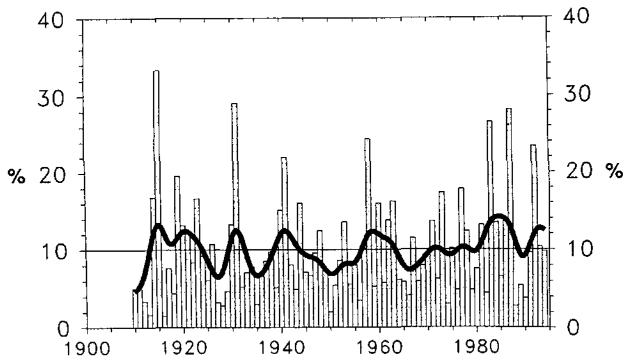

FIG. 12. Percentage of the conterminous U.S. area with much below normal day-to-day temperature differences.

a. The Climate Extremes Index

The U.S. CEI is the annual arithmetic average of the following five indicators of the percentage of the conterminous U.S. area:

1) The sum of (a) percentage of the United States with maximum temperatures much below normal and (b) percentage of the United States with maximum temperatures much above normal.
2) The sum of (a) percentage of the United States with minimum temperatures much below normal and (b) percentage of the United States with minimum temperatures much above normal.
3) The sum of (a) percentage of the United States in severe drought (equivalent to the lowest tenth percentile) based on the PDSI and (b) percentage of the United States with severe moisture surplus (equivalent to the highest tenth percentile) based on the PDSI.
4) Twice the value of the percentage of the United States with a much greater than normal proportion of precipitation derived from extreme (more than 2 in. or 50.8 mm) 1-day precipitation events.
5) The sum of (a) percentage of the United States with a much greater than normal number of days with precipitation and (b) percentage of the United States with a much greater than normal number of days without precipitation.

In each case, we define much above (below) normal or extreme conditions as those falling in the upper- (lower) tenth percentile of the local, century-long period of record. In any given year, each of the five indicators has an expected value of 20%, in that 10% of all observed values should fall, in the long-term average, in each tenth percentile, and there are two such sets in each indicator. An extremely high value in any one of the five indicators does not exclude extremely high values for the others. In fact, for the maximum and minimum temperature indicators (1 and 2 listed above) there is usually, but not always, a close correspondence between the two. The fourth indicator, related to extreme precipitation events, has an opposite phase that cannot be considered extreme: the fraction of the country with a much below normal percentage of annual precipitation derived from extreme (i.e., zero) 1-day precipitation amounts. Hence, the fourth indicator is multiplied by twice its value to give it an expected value of 20%, comparable to the other indicators. Overall, the CEI gives slightly more weight to precipitation extremes than to extremes of temperature. A value of 0% for the CEI, the lower limit, indicates that no portion of the country was subject to any of the extremes of temperature or precipitation considered in the index. In contrast, a value of 100% would mean that the entire country had extreme conditions throughout the year for each of the five indicators, a virtually impossible scenario. The long-term variation or change of this index represents the tendency for extremes of climate to either decrease, increase, or remain the same. Although we focus on an annual CEI and do not produce a "seasonal" CEI, which may be more appropriate for some impact studies or to explore the processes leading to changes and variations in the index, the CEI is constructed such that seasonal values can easily be calculated.

The century-long record of the CEI depicted in Fig. 13 demonstrates that the climate of the United States in this period has included large decadal fluctuations of climate extremes. Since about 1976, the time when

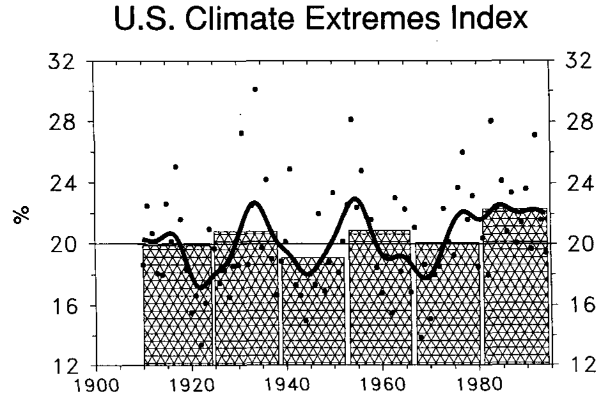

FIG. 13. An annual U.S. Climate Extremes Index. Dots represent annual values, the smooth curve is a 21-point binomial filter, and the bars represent 14-year averages.

the atmospheric circulation over the Pacific and North America underwent a significant change (Trenberth 1990; Trenberth and Hurrell 1994), the CEI has averaged about 1.5% higher than the average of the previous 65 years. This is equivalent to a persistent increase of extreme events covering an area somewhat larger than the state of Indiana. Other notable times of extreme climate variations include the 1930s and 1950s, but the more recent spell of extreme climate variations is of longer duration. This increase in extremes is related primarily to the increase in three precipitation indicators: the frequency of long-term drought severity and moisture excess, the frequency of extreme 1-day precipitation events, and a much greater than normal number of days with precipitation. The increase in climate extremes over the past 15 to 20 years is not, however, of sufficient persistence and magnitude to suggest that the climate really has changed. Such a change simply due to natural year-to-year variability is not unexpected (Table 3). Depending on the model selected, the range of P values extends from 0.10 to 0.21. One could argue that since the impacts or damages associated with extremes go up exponentially, the CEI should be nonlinearly scaled, but the appropriate scaling is uncertain. Clearly, this would further emphasize the significance of the recent increase in extreme events.

b. *The U.S. Greenhouse Climate Response Index*

The U.S. Greenhouse Climate Response Index (GCRI) is composed of a set of anticipated greenhouse climate response indicators. It is intended as a means of early detection and monitoring of *anticipated* greenhouse-induced climate change as applied to conditions in the United States. Other anthropogenic influences on climate, such as the cooling effects of sulfate aerosols (Santer et al. 1995; Karl et al. 1995b) and natural climate change mechanisms, will either enhance or reduce the GCRI. It is worth noting, however, that in the United States there was a negligible net change of anthropogenic emissions of sulfur dioxide (which can cause sulfate-induced smog) between 1950 and 1993.

The U.S. GCRI is calculated from the annual arithmetic average of the following five indicators of the percentage of the conterminous U.S. area:

1) The percentage of the United States with much above normal mean temperature (minimum temperature times 0.525 plus maximum temperature times 0.475).
2) The percentage of the United States with much above normal precipitation during the months of October through April (the cold season).
3) The percentage of the United States in extreme or severe drought during the months of May through September (the warm season).
4) The percentage of the United States with a much greater than normal proportion of precipitation derived from extreme 1-day precipitation events (exceeding 2 in. or 50.8 mm).
5) The percentage of the United States with much below normal day-to-day temperature differences.

Each of these five indicators defines an anticipated response of the U.S. climate related to increases of atmospheric greenhouse gases derived from the Intergovernmental Panel on Climate Change (1990, 1992, 1995). In addition to its role in monitoring for anticipated climate responses, another reason for developing a U.S. GCRI is to obtain additional information by analyzing multiple, mostly independent parameters, each of which is expected to respond to increases of greenhouse gases and/or temperatures. Due to data deficiencies, only mean temperature has been analyzed and related to the greenhouse effect on global space scales (IPCC 1992). So, although a "United States only" analysis suffers from limited areal extent, by using five mostly independent indicators it does complement global greenhouse detection analyses with limited dimensionality in variate selection. The correlation matrix (Table 4) of detrended indicators reveals that most indicators are independent or

TABLE 3. Same as Table 1 for this century except for indices. The hypotheses tested is that trends of extremes are not stationary; trends in the greenhouse response are not stationary and are positive.

Indices	Sign of trend	Model order ARMA (p, q)	P-value of trend
U.S. Climate Extremes Index	+	(1, 1)/(1, 0)	0.21/0.10
U.S. Greenhouse Response Index (weighted)	+	(1, 2)/(1, 1)	0.08/0.05
U.S. Greenhouse Response Index (unweighted)	+	(1, 1)/(0, 1)	0.04/0.01

only weakly related to each other. The major exception is the correlation between temperature and drought during the warm season. This latter relationship, however, still explains only 36% of the common variance between temperature and warm season drought.

Each indicator has an expected value in any given year of 10%. For the first indicator, we use a slightly heavier weight for the minimum temperature compared to the maximum (10% more), which is consistent expected greenhouse forcing (IPCC 1990, 1992). Each indicator focuses on the highest or lowest tenth percentile of the distribution to ensure that changes in the indicators reflect events that are often noticed by the general public as well as by policy makers. The choice of an upper or lower decile is based on the expected trend of the quantity under consideration.

A question arises about the appropriate emphasis or weight to assign to each of the five indicators. We show both weighted (Fig. 14a) and unweighted (Fig. 14b—all five indicators equally weighted) versions of the GCRI and note that differences between the weighted and unweighted versions are relatively minor (Table 3). The weights used reflect our subjective estimate of the relative confidence placed on anticipated greenhouse-induced changes in U.S. climate: a value of 5 for the first indicator (temperature); 4 for precipitation; and 3, 2, and 1 for indicators (3), (4), and (5), respectively. Since the expected value for the GCRI for any given year is 10%, we depict this as a horizontal line in both the weighted and unweighted version of the GCRI, reflecting a time invariant climate.

Based on the overall increase of the GCRI, it can be concluded that the changes are consistent with the general trends anticipated from a greenhouse-enhanced climate. Moreover, since 1980, the unweighted and weighted GCRIs have averaged 12.8% and 13.3%, respectively, which is 2.8% and 3.3% higher than expected. In terms of relative effect, a change of this magnitude corresponds to an area somewhat greater than the combined areas of Indiana, Illinois, and Ohio.

TABLE 4. Correlation coefficients among GCRI indicators (after removal of the trend). An asterisk reflects statistically significant (0.05) correlations.

Variables	Mean temperature	Cold season precipitation	Drought intensity	Extreme precipitation	Temperature variability
Mean temperature	1.00	—	—	—	—
Cold season precipitation	–.15	1.00	—	—	—
Drought intensity	0.60*	–0.32*	1.00	—	—
Extreme precipitation	–0.03	0.12	–0.06	1.00	—
Temperature variability	0.26*	0.24*	–0.07	–0.08	1.00

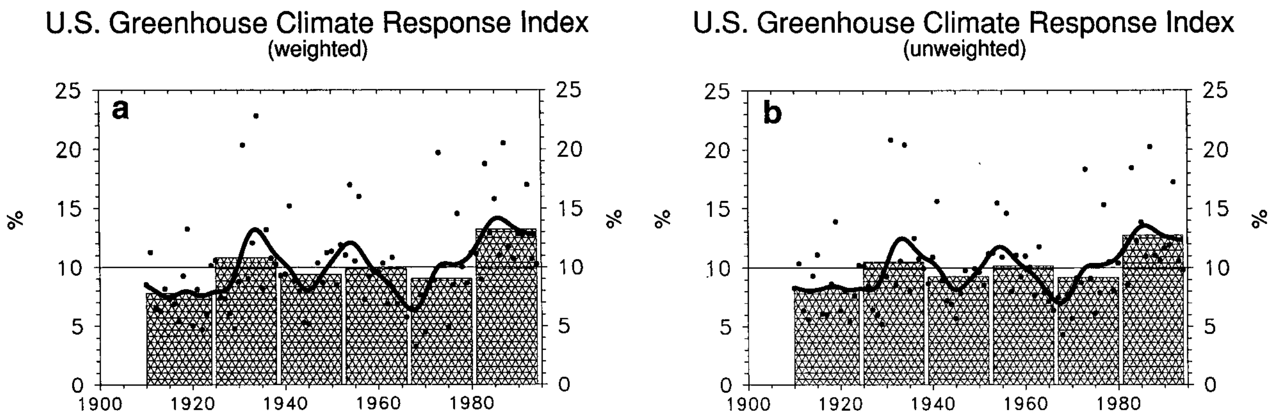

FIG. 14. Same as Fig. 13 except for the annual U.S. Greenhouse Climate Response Index based on greenhouse climate response indicators; (a) weighted and (b) unweighted.

At the same time, however, statistical analysis indicates that because the change is neither large enough nor consistent enough through time, it may not be prudent to unequivocally reject the possibility (roughly a 5% chance) that the increase is a random variation of a stationary climate (Table 3). To test the sensitivity of the P value to the model selected, the full range of ARMA models of orders 1 to 4 were simulated: P values ranged from 0.01 to 0.20 and from 0.01 to 0.09 for the unweighted and weighted version of the GCRI.

7. Discussion and conclusions

A framework has been developed that can be used by climatologists to express multidimensional changes in an integrated and informative manner. We present two indices composed of specific indicators—a Climate Extremes Index and a Greenhouse Climate Response Index. The content of these indices are unlikely to be totally static. New indicators may be added as our databases improve (e.g., winds, hail, tornadoes, etc.), and information increases regarding the details of the climate response to increases in greenhouse gases. Moreover, as other forcings become better understood (e.g., sulfate aerosols), other indices will surely emerge.

At the present time, the trends of several indicators stand out most conspicuously. These include the rather steady increase in precipitation derived from extreme 1-day precipitation events, the decrease in area affected by much below normal maximum temperatures, the increase in area with much above normal cold season precipitation, and the increased area of the country with more frequent frequency of days with precipitation. Trends in other indicators of climate change are not now sufficiently large or persistent to be considered *strongly* suggestive of a changing climate. Nonetheless, real changes in climate remain the most likely explanation for the most conspicuous changes. Some of the indicators had seemingly significant changes during the late 1970s and have more or less remained at these levels to the present time. Other surface climate change indicators (e.g., proportion of the country affected by extreme or severe warm season drought) reflect the kind of climatic variability that is completely consistent with the premise of a stable or unchanging climate.

It is noteworthy that the increase in temperature across the United States is slightly smaller than the global increase of temperature. An increase in minimum temperature relative to the maximum is also reflected in many other countries of the Northern Hemisphere (Karl et al. 1991, 1993c). Worldwide land precipitation has increased only about 1% over the twentieth century (IPCC 1995), but this is because high latitude increases have been balanced by low-latitude decreases. By comparison, the change in precipitation in the United States is still relatively moderate compared to some of the increases and decreases at other latitudes. Decreases in the day-to-day differences of temperature observed in the United States are also apparent in China and Russia, the other large countries analyzed as of this date (Karl et al. 1995c). The persistent increase in the proportion of precipitation derived from extremely heavy precipitation has not been detected in these countries, although homogeneous records are much shorter. In northeast Australia, however, significant increases in extreme precipitation events have been detected by Suppiah and Hennessy (1995).

The Climate Extremes Index, defined by an aggregate set of conventional climate extremes indicators, supports the notion that the climate of the United States has become more extreme in recent decades. Yet the magnitude and persistence of the changes are not now large enough to conclude that the climate has systematically changed to a more extreme state as opposed to fluctuating about a near-stable state. The U.S. Greenhouse Climate Response Index, composed of indicators that measure the changes of U.S. climate that are expected to follow increased emissions of greenhouse gases, reflects twentieth century trends that are consistent with expectations. Moreover, all five indicators reflect positive trends consistent with greenhouse projections, with two of them reflecting highly significant trends. Still, the rate of change of the GCRI, as with the CEI, is not large enough to unequivocally reject the possibility that the increase may have resulted from other factors, including natural climate variability, although this is not a likely explanation (about a 5% chance). Moreover, the hypothesis tested is simply that the trend in the GCRI is nonzero and positive. The sensitivity of the climate system to anthropogenic greenhouse forcing is not addressed by this test. By analogy, the circumstantial evidence for linking greenhouse projected change in the U.S. climate and observed changes may be adequate in a civil court but not in a criminal conviction (at least one juror would still have reasonable doubts).

Both the CEI and the U.S. GCRI increased rather abruptly during the 1970s [although two-phase regression analysis (Solow 1987) does not indicate a significant change point in the series] at a time of major circulation changes over the Pacific Ocean and North America. Moreover, since the winter of 1976–77, the frequency and intensity of El Niño–Southern Oscillation events have increased relative to previous decades. During these years, sea surface temperatures in the central and eastern equatorial Pacific have remained anomalously warm. Such events have been directly linked to increased precipitation and reduced winter temperatures along the Gulf Coast of the United States (Ropelewski and Halpert 1987; Halpert and Ropelewski 1992). During the late 1970s and into the 1980s (whether this has continued in the 1990s is less apparent), a large-scale redistribution of atmospheric mass took place in the North Pacific, associated with a change of the jet stream over the North Pacific and North America. There is little doubt that the increase in the indices is at least partially related to these circulation variations, but analyses indicate that they are not a dominant factor. For example, we have calculated the coherence of the Southern Oscillation Index (SOI) with the GCRI but find no statistically significant relationships. We do find a peak in the cospectrum that is almost significant (at the 0.10 level, but with only 2% to 3% of the covariance explained) at timescales of 4 to 6 years, the approximate recurrence interval of ENSO events. A weak, nonsignificant relationship is also evident in a 1-year lag with negative values of the SOI leading the GCRI toward higher values. It must be acknowledged that the role of increased anthropogenic greenhouse gas concentrations in such circulation variations is poorly understood. Since the indices are influenced by natural changes and variations that can either add or subtract from any underlying long-term anthropogenic-induced change, it will be important to carefully monitor the indices over the next decade to see if they sustain their incipient trends or return to previous levels. It will also be important to continue improving the indices and the homogeneity of the records that constitute the indices. Such efforts are critical for a better understanding of climate, how it changes, and how these changes can affect our own lives and well-being.

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